PERFORMANCE OF THE HERMES-III LASER-TRIGGERED GAS SWITCHES*

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Abstract

This paper reports the performance of the SF_6 insulated, multistage, laser-triggered gas switch used in the Hermes-III accelerator.[1] In this accelerator, 20 of these switches are used to transfer energy from intermediate energy storage water-dielectric capacitors to the pulse forming lines (PFLs). Approximately 8,000 laser-triggered switch shots have been taken with seven prefires. Nearly 70% of these shots have been at nominal operating parameters. The average first-to-last spread in firing times for 20 switches is approximately 8 ns. Removal of systematic differences reduces this spread to ~6 ns. This spread implies a one-sigma jitter for a single switch of <2 ns at 70-75% of self-breakdown voltage. Results show that the jitter does not change significantly over an operating range of 70-90% of self-breakdown. In addition, the jitter is insensitive to the factor of two variation in the laser energy delivered to the various switches by the optical system. A detailed summary on the performance, reliability, and maintenance of the switches and optical system is presented. Initial results of a study to investigate the performance of these switches under varying laser trigger conditions is also presented.

Introduction

Twenty SF_6-insulated, multistage, laser-triggered gas switches are used in the Hermes III accelerator, shown in Fig. 1, to transfer energy from the intermediate energy storage capacitors to the PFLs. Each switch transfers the energy from one 19-nF, water dielectric capacitor to four 5-Ω, 20-ns (one-way transit) PFLs in 180-200 ns. The water capacitor is charged to a peak voltage of 2.2-2.4 MV in approximately 1 μs. Laser triggering the gas switches, with approximately 15-mJ KrF laser energy per switch, provides the synchronization for the charging of the 80 PFLs.

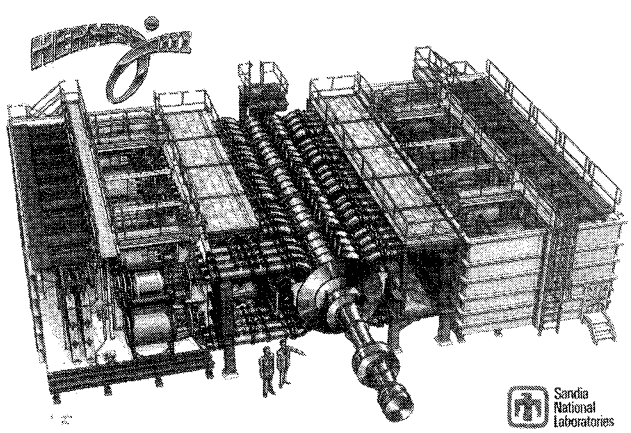

Fig. 1 Artist's drawing of Hermes III

Gas Switch Description

The Hermes-III multistage gas switch is shown in Fig. 2. A detailed description of the gas switch has been previously presented.[2] Figure 3 is a photograph of a single gas switch-intermediate store capacitor module, as installed in Hermes III. The triggering laser beam is transported to the oil-immersed switch through a SF_6-filled acrylic tube that is connected to the gas switch at one end and to the oil tank wall at the other end. The laser beam enters the switch's triggered section through the hole in the electrode and is focused near the middle of the gap. The focused beam creates a low level of ionization throughout the length of the gap, initiating closure of this section of the switch. This process triggers closure of the remaining portion of the gap. After the triggered gap has closed, the electric fields redistribute themselves causing the untriggered gaps to be overvolted and to close rapidly. Substantial current flows through the switch only after the last gap has closed.

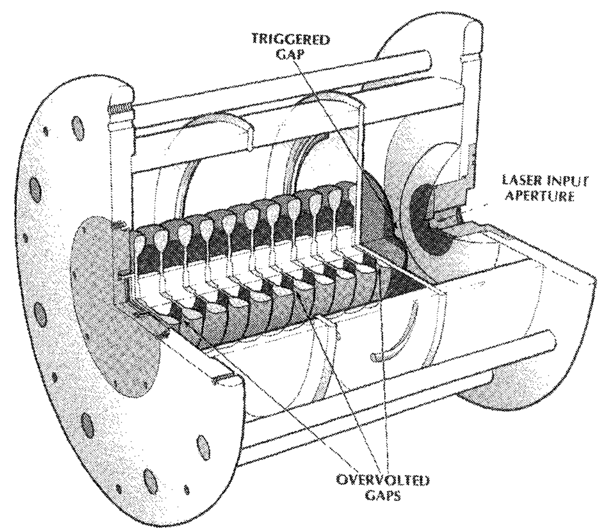

Fig. 2 Drawing of Hermes III laser triggered gas switch

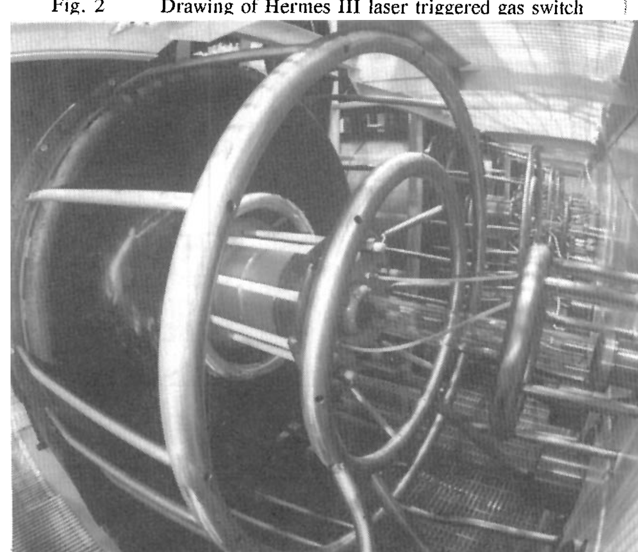

Fig. 3 Photograph of gas switch-water capacitor module

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14. ABSTRACT
This paper reports the performance of the SF6 insulated, multistage, laser-triggered gas switch used in the Hermes-III accelerator.' In this accelerator, 20 of these switches are used to transfer energy from intermediate energy storage waterdielectric capacitors to the pulse fmming lines (PFLs). Approximately 8,000 laser-triggered switch shots have been taken with seven prefires. Nearly 70% of these shots have been at nominal operating parameters. The average first-tolast spread in firing times for 20 switches is approximately 8 ns. Removal of systematic differences reduces this spread to -6 ns. This spread implies a one-sigma jitter for a single switch of < 2 ns at 70-75% of self-breakdown voltage. Results show that the jitter does not change significantly over an operating range of 70-90% of self-breakdown.

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Laser Trigger System

Hermes III uses a commercially available 0.9-J KrF laser to trigger its twenty gas switches. The laser output has a FWHM of approximately 30 ns. Laser triggering of the switches is accomplished by optically splitting the single KrF beam into 20 beamlets, ranging in energy from 10-30 mJ. Each beamlet is focused into its respective switch. These switches are triggered in five groups of four, with all switches in each group being triggered simultaneously with one another. The delay between adjacent groups of four switches, proceeding from the low voltage end of the accelerator to the high voltage end, is 8.5 ns and is fixed by the path length of each beamlet. The optical path contains "trombone" mirrors that allow ±5-ns adjustments to the laser pulse arrival time at the switches. A detailed explanation of the laser triggering system has been previously presented.[3]

System Performance

Certain characteristics are recognized as being desirable for a laser-triggered switch system. These characteristics are: (a) low jitter, (b) minimum sensitivity of switch closure time to switch voltage and laser energy, (c) low switch prefire rate, (d) low laser energy requirements, (e) low maintenance, (f) high reliability, and (g) efficient laser beam transport and optical-alignment systems. Each of these characteristics will be discussed in describing the performance achieved by the Hermes-III gas switches.

Figure 4 shows the gas switch spreads, first to last, as recorded from ~400 accelerator shots on Hermes III at nominal operating parameters, 2.2-2.4 MV across the switch, and a pressure of 2300 Torr. The average spread for twenty switches is approximately 8 ns, and includes systematic timing differences between the switches. The distribution of the data is closely approximated by a Gaussian function with a mean value of 8 ns and a one-sigma standard deviation of 2 ns.

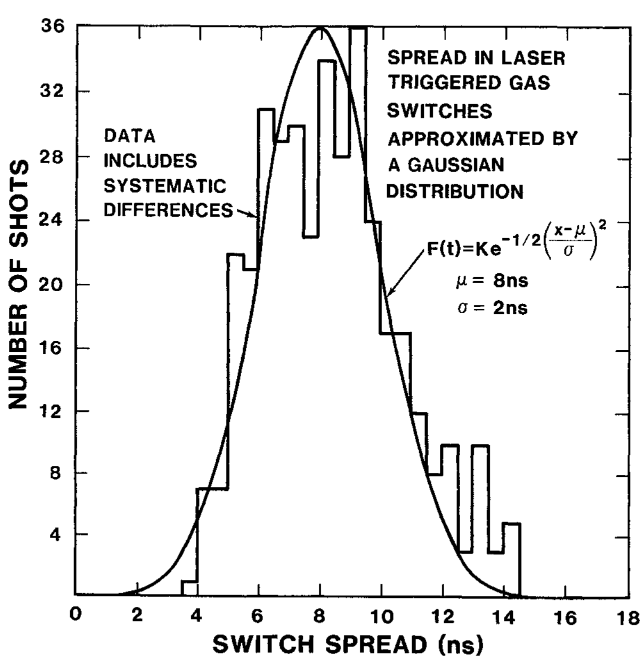

Fig. 4 First-to-last gas switch spread for 20 switches obtained from 400 shots

Spreads of 6 ns or less were obtained when the optical path lengths of individual beamlets were adjusted to remove or reduce systematic timing differences, as shown in Fig. 5.

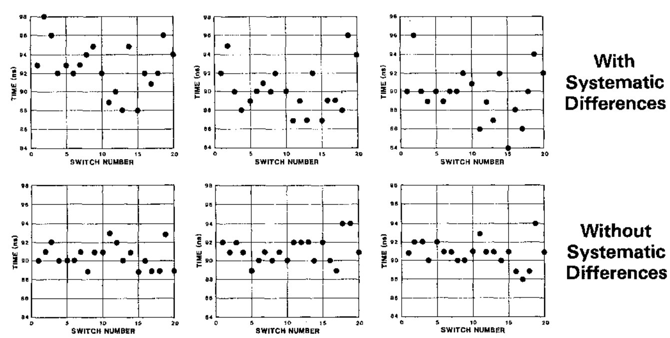

Fig. 5 Removing systematic differences reduces measured gas switch spread

This spread corresponds to an rms jitter for a single gas switch of <2 ns and meets the design criteria set for Hermes-III operation.[1] The system's performance has been stable and reproducible and does not require the continual monitoring of operational settings. The gas switch is fairly insensitive to a range of switch voltages from 75-90% of self-breakdown voltage, as shown in Fig. 6. Sensitivity to variations in laser energy and pulsewidth will be discussed later.

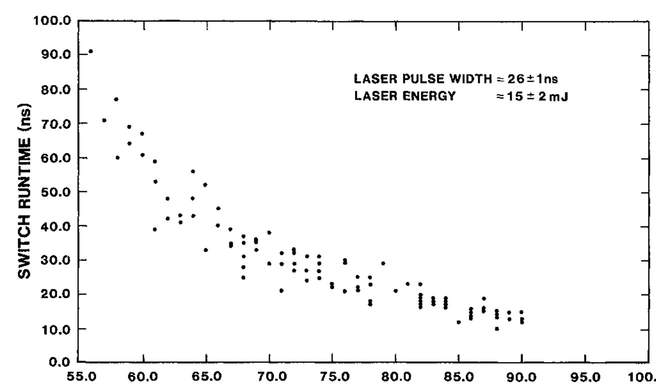

Fig. 6 Measured switch run time for full pulsewidth, full energy laser pulse using point of steepest slope on laser pulse as reference

Over a period of ~400 shots taken at nominal operational conditions, only 7 prefires occurred, producing a prefire rate of 1.8%. Previous analysis of the self-breakdown characteristics for this switch predicted a 2% prefire rate for an ensemble of twenty switches on Hermes III.[2] In all of the prefire cases, only one of the twenty switches was early. The total current delivered to the diode was decreased by 10% or less. These shots, though lower than normal, still produced usable output for simulation purposes. During this same period, six late switch closures were observed. Post-shot examination revealed that the laser beam was misaligned with the input aperture to the switch, thus resulting in the switches firing late.

The optical train from the KrF laser to the gas switches consists of a series of reflectors, beamsplitters, and focusing lenses coated for maximum reflectance or transmission at 248 nm. All of these components have remained within 6% of measurements made prior to installation in the triggering system.

Maintenance and Reliability

During the period from April 1987 to the present, all of the gas switches in Hermes III have been removed from the accelerator at least once for cleaning or repairs. Shortly after the initial installation of these switches into Hermes III, a sudden influx of insulator failures occurred as a result of metal shavings migrating out of tapped holes onto insulating surfaces. Once the shavings were removed, switch lifetime increased dramatically. A number of switches have been replaced because of occasional insulator "tracking." Switches have also been removed because of gas leaks and sudden changes in performance. Switch removal and replacement, however, does not translate to significant accelerator downtime.

The laser-beam access tubes have been modified since being installed in Hermes III. Early in the accelerator checkout phase, the epoxy-filled, metal-to-plastic joints began to leak SF_6. It was discovered that the mechanical shock associated with the firing of the accelerator was cracking the epoxy bond. Modifications to the metal collars at each end of the acrylic tubes eliminated this failure mode.

All of the optical components are contained within dust-tight enclosures; and while each is readily accessible for cleaning, most of the optics have never been serviced. Recorded data, such as that in Fig. 4, does not indicate degradation in accelerator performance due to energy losses in the laser triggering system as a result of "dirty" optics.

The KrF laser used in the triggering system has been in operation for approximately three years. The laser has been aligned and cleaned once during this period. The thyratron trigger within the laser has been replaced several times to eliminate pre-firing of the laser. The prefire problem has not been completely cleared up, however, and is still being investigated. Presently, both the oscillator and amplifier cavities within the laser are leaking gas. This situation will be resolved during the next scheduled accelerator downtime. Neither of these problems has prevented the required functioning of the laser during Hermes-III experiments.

Dependence on Laser Pulse Width and Energy

In order to further understand the relationship between the laser pulse width and/or energy and the switch run time, a switch similar to that shown in Fig. 2 has been installed in the Subsystem Test Facility (STF), in a configuration duplicating that of Hermes III.[1] The triggered gap spacing in this switch was decreased from 4.2 cm to 3.7 cm to look at self-breakdown behavior. No significant change was seen.

A KrF laser similar to the one used in Hermes III was used for these tests. The nominal laser output has a pulse width (FWHM) of 26 ns. The output was attenuated to 15 mJ, and was used to conduct a series of tests on STF to verify data previously acquired under the same conditions.[2] The percent of self-breakdown voltage was varied while measuring the resultant switch run time. The past and present data agreed quite well. Figure 6 is a combination of the two data sets. Switch run time is derived by measuring the difference between the arrival time of the laser pulse at the gas switch and the time of gas switch closure, as shown in Fig. 7.

Having verified "standard" Hermes-III triggered switch behavior, we then decreased the pulse width of the laser output while maintaining the same pulse energy. This shortening of the laser pulse was accomplished by means of a

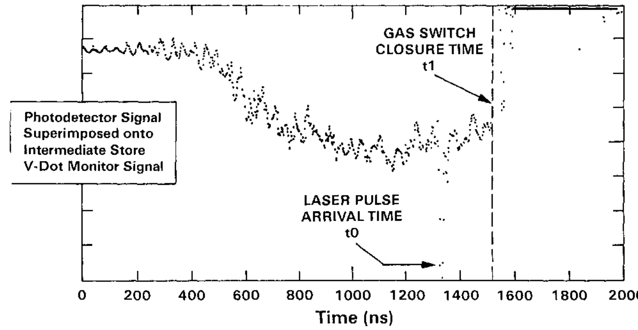

Fig. 7 Method for measuring switch run time

plasma-switching scheme similar to that reported previously by Lou[4] and is shown in Fig. 8. The KrF laser beam was divided into two equal beams as it exited the laser. Fifty percent of the original beam followed path A, while the other 50% followed path B. The path A beam was brought to a focus in front of a graphite wafer, skimming the surface of the graphite, and then recollimated by a second lens. A few percent of the beam was then directed onto a photodetector to monitor pulse shape and energy. The path B beam travelled a shorter path before being focused by an 86-cm focal length lens onto the graphite wafer in the area where beam A

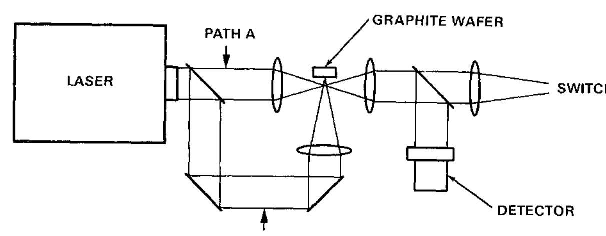

Fig. 8 Experimental arrangement used to shorten laser pulses

contacted its surface. This focused energy created a plasma "cloud," which would effectively shutter the path A beam as it passed through that area. The shortened pulse was then focused between the two electrodes in the triggered section of the switch. Figure 9 shows the results. The shortened

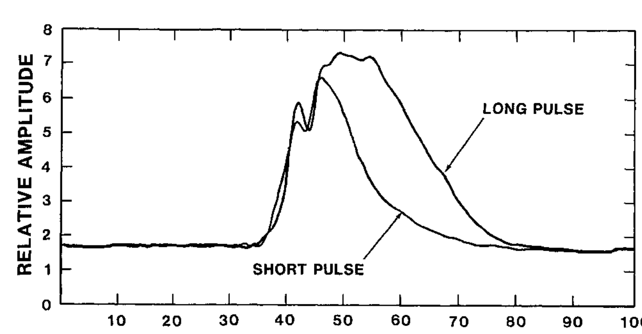

Fig. 9 Comparison of full and shortened laser pulses

pulse had a width of 15-ns (±2 ns) FWHM at 15-mJ (±2 mJ) energy. Switch performance data taken with the shortened pulse is shown in Fig. 10. Comparing this data to the data shown in Fig. 6, note that the performance of the switch was not affected by the decrease in pulse width.

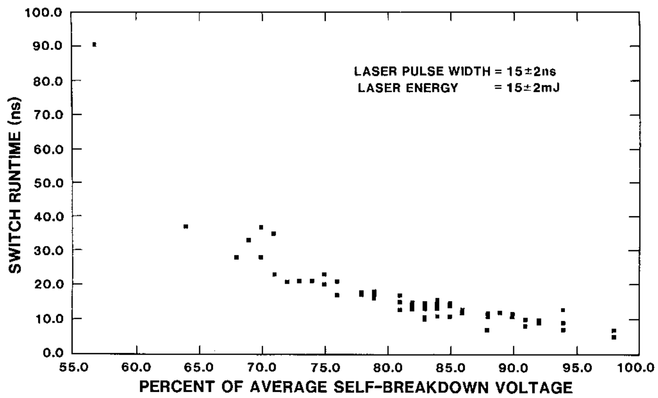

Fig. 10 Measured switch run time for shortened, full energy laser pulse using point of steepest slope on pulse as reference

Having shortened the laser pulse, the pulse energy was then decreased by a factor of two. The resultant laser trigger pulse had a width of 15 ns (±2 ns) FWHM at 7-mJ (±2 mJ) energy. Figure 11 shows the effect that this modification to the trigger pulse had on gas switch performance. Again, note that the run time and jitter of the switch above 65% of self-breakdown were not appreciably affected by this change.

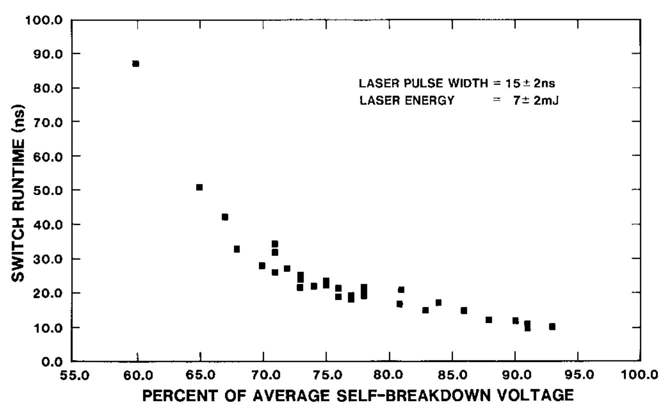

Fig. 11 Measured switch run time for shortened, half energy laser pulses using point of steepest slope on pulse as reference

The switch run time data presented above represents the time required for all stages of the switch to close. A separate experiment was performed to measure the closure time of the triggered section alone. The ten self-closing gaps of the switch were shorted for these tests, and a ~10-Ω resistor was placed in parallel with the water capacitor to reduce the peak voltage across the switch. Data was obtained to establish the self-breakdown characteristics in this configuration. The switch run time was then measured using the "standard" laser pulse width and energy, and is shown in Fig. 12. The switch run time on this figure was calculated from the arrival of the laser pulse at the switch. The data in previous figures was calculated using the point of steepest slope of the laser pulse as the zero reference. The point of steepest slope occurs ~5 ns after the start of the laser pulse. This change was made to avoid having negative values of run time in Fig. 12. At 75% of self-breakdown voltage, the triggered gap closes ~8 ns into the laser pulse. This may explain why the triggered performance of the full switch is not strongly dependent on changes to the laser trigger energy and pulse width. The data also shows that control of the triggered gap is maintained down to ~35% of self-breakdown voltage versus ~65% for the full switch. Closure of the switch multi-gap self-breakdown section is apparently controlling the observed switch performance on Hermes III.

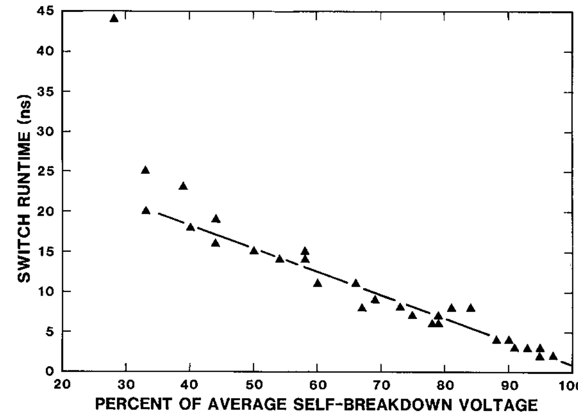

Fig. 12 Measured triggered gap run time for full pulsewidth, fu energy laser pulse using start of pulse as reference

Conclusion

The Hermes-III laser triggering system is operating reliably, and has met or exceeded design specifications. After initial problems resulting from particle contamination were resolved, the system has proven very robust and has required little maintenance. Tests performed on STF indicate that significant reduction in the laser pulse width and energy are possible, while maintaining low jitter performance.

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